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THE OBJECTIVE MEASUREMENT OF THE ATTENUATION OF HEARING PROTECTORS OF THE CIRCUMAURAL TYPE

by

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SUMMARY

Measurements have been made of the attenuation of five circumaural hearing protectors using dummy heads of three different designs. Results illustrate the variability on repeated attachment of the protectors to the dummy heads, and the effect of geometrical factors in the design of the latter.

The results are also compared with the subjective calibration of the same five earmuffs carried out previously under directly comparable conditions. Attenuation measured on the dummy heads was consistently greater than that found subjectively, but was highly correlated to it at frequencies up to 2 kHz. This correlation is used to demonstrate that results in good agreement with subjective values may be predictable from objective measurements in simple test conditions.

Contents | Page No.

1. INTRODUCTION

Current standards for the measurement of acoustic attenuation of hearing protectors are almost all based upon the method of 'real-ear attenuation at threshold' (1,2). The principle employed is to measure two thresholds of hearing on each of a group of subjects, one with the hearing protector being worn, the other with it removed. The attenuation at a particular frequency is then taken as the mean difference between the two hearing threshold levels.

The method has a number of practical disadvantages, notably its need for a special (and expensive) acoustic room with very low ambient noise, and its time-consuming nature resulting from the need for an adequate number of subjects to take part in the tests. It may also be criticised from a methodological point of view in that the threshold test, involving as it does very different levels from those in which protectors are worn in actual use, may give misleading results due to certain complicating factors. One of these is a possible error arising from physiological noise generated under the earmuff: by raising the closed-ear threshold, this may give values of hearing protector attenuation which are inflated by a few decibels at low frequencies. Another is the possible existence of a level-dependent attenuation due to non-linear performance.

For these reasons much effort has gone into the search for an alternative 'objective' or 'physical' method which would be simple and quick, and which would call for a minimum of special facilities. To supplant the real-ear threshold method, the results obtained would need to be closely and reliably related to those determined subjectively, and have good repeatability. One of the simplest objective methods of measuring the attenuation of hearing protectors of the external muff type involves the use of an artificial ear or hard-walled coupler of the type employed for measurement of the frequency response of earphones, and in audiometric standardization. There are reports on this method by Johnston (3), who used a wide-band artificial ear of the the type described in IEC publication 318 (4), and by Whitham and Martin (5) who used an IEC 303 reference coupler (6). The latter consists of a cylindrical hard-walled cavity of about 6 cm^3 volume terminated at its base by a one-inch standard condenser microphone. These instruments, normally used with supra-aural earphones, were adapted by fitting a flat plate of diameter sufficient to accommodate hearing protectors of the circumaural type.

The advantage of ready availability of the artificial ear and coupler used in these studies and the simplicity of the approach is somewhat offset by the lack of a convenient means of applying the correct static force. This is best supplied by the spring headband, with the earcups separated by the width of the human head, and leads to the idea of an artificial head whose width dimension is adjustable to ensure the correct mechanical loading of the hearing protector. Several artificial heads of varying complexity have been proposed in recent years (7,8,9,10,11). They range from simple modifications of artificial ears to devices which simulate such variables as head width, angle, surface contour and hair length. One device makes use of an artificial pinna. A significant omission, however, is any attempt to simulate the effect of bone conduction, which is known to set an upper limit to the attenuation of hearing protectors on human heads.

With all the above-mentioned devices, the relevant quantity to be compared with the real ear attenuation is the insertion loss - the difference in sound pressure level registered by a microphone within the device, with and without the hearing protector in place.

None of the designs has been found acceptable as a substitute for subjective testing and it seems that adequate modelling of the many parameters remains a distant goal. Notwithstanding this, the need already exists for an objective method of measurement for the more limited purposes of production quality control, for development work, and for checks of acoustical performance before and after use (durability testing). For these purposes a certain loss of fidelity in simulation may be acceptable provided the device does not produce perverse results. The dummy head specified in the supplemental method of American Standard ASA STD 1-1975 (2) is of this nature, and the aim of the experimental work described here was to assess the usefulness of this and some other devices and to evaluate their limitations in the testing of circumaural hearing protectors.

2. OUTLINE OF EXPERIMENTS

The conduct of the experiments was determined by a number of events, not all planned. The original purpose was to appraise the American device, because this enjoyed the advantages of commercial availability and of having been written into a national standard. Detailed tests on a purchased specimen were therefore conducted first, using five pairs of ear protectors whose subjective performance had been measured previously. The results of this phase are given in Section 6.1.

Afterwards, we thought it worth investigating whether all of the features of the device were really necessary. In particular would the results be much affected by eliminating the artificial (plastic) skin? Would the repeatability of tests suffer? If not, this feature which complicates the specification might be dropped, at least for purposes of routine measurement. Secondly, is the overall geometry of the device critical or could a more elementary solid figure be substituted? While these aspects were being explored, Working Group 17 of ISO/TC43/SC1, which had begun work on a similar project, proposed a certain geometry (cylindrical with oblique end faces) and the opportunity was taken to test a device of this type. Another shape tried was based on a simple rectangular box.

Unfortunately a fault developed in one of the calibrated ear muffs following the conclusion of the work on the unmodified American device. We therefore have not attempted a balanced design of tests across devices, but have explored the above-mentioned factors independently.

Section 6.2 is devoted to the effect of simplifying the device or substituting other devices with simpler geometry. Supplementary tests, on azimuthal variation of performance and the advantage of the diffuse field over a single sound source, are reported in Section 6.3.

3. EQUIPMENT TESTED

3.1 <u>Hearing protectors</u>

Five hearing protectors which had previously been tested (12) using the subjective real-ear attenuation at threshold method of BS 5108 (1) were used in these experiments. For convenience some details are repeated in Table 1. Also shown is the measured force exerted by the headband when the earcups were separated by 143.5 mm.

The device which failed during the investigation was type E. The replacement is designated E2.

Table 1

Hearing Protectors

Type	Seal	Weight (g)	Headband force (N)
A	Foam	190	12.3
C	Foam	310	10.5
D	Fluid	360	11.3
E	Fluid	200	8.3
F	Foam	310	9.4

3.2 Artificial heads

The American Standard specifies a device, one realization of which is made commercially in USA by Unipolycon and known as Dummy Head Model 801. Its critical surface dimensions conform to those specified in the American Standard (Fig 1 a) which are representative of an American population. The device is made of solid cast and machined aluminium type 40E and constructed in left and right halves which are held together with four Allen screws, the mating surfaces being thinly coated with silicone grease. A one-inch piezo-electric microphone (Brüel & Kjaer Type 4117) is grease-sealed in a hole bored in one side of the head and is backed by open-pore polyfoam. A small groove milled in one of the mating surfaces accommodates the microphone cable and is sealed with grease. The side surfaces of the head upon which the earcups seat, and the top surface which supports the headband, are covered with artificial flesh in the form of cast vinyl pads 6 mm thick. These are held in place with a thin film of grease. The microphone is positioned so that the surface of its protective grid is flush with the outer surface of the artificial skin, a circular hole having been cut in one of the pads to allow this. The head assembly is supported on 4 anti-vibration mounts

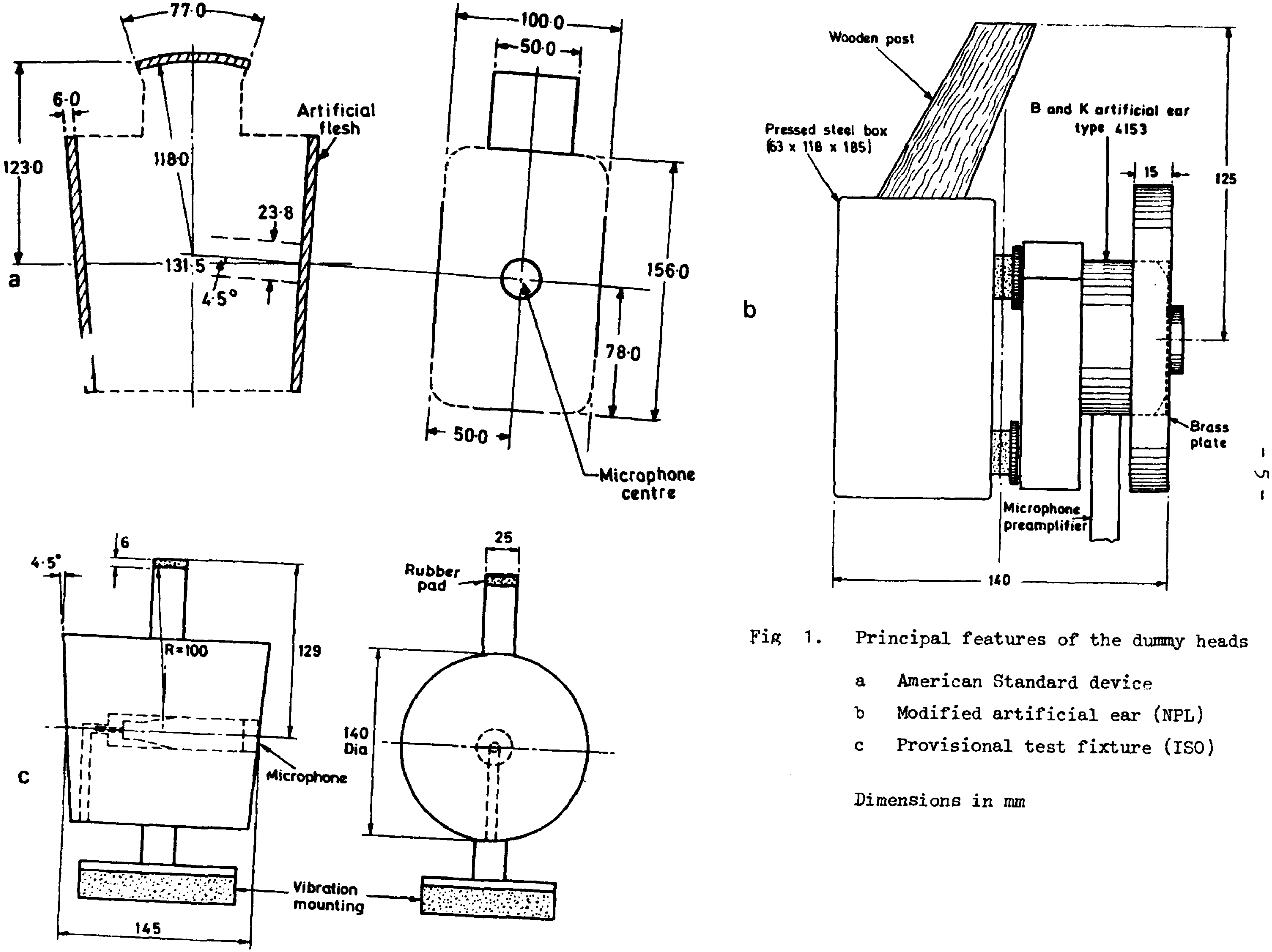

Fig 1. Principal features of the dummy heads

a American Standard device

b Modified artificial ear (NPL)

c Provisional test fixture (ISO)

Dimensions in mm

(resonance frequency about 15 Hz) attached to a baseplate, the whole being supported by an adjustable microphone stand.

The first of the simplified devices is illustrated in Fig 1 b. It is based on a rectangular box and makes no pretensions to simulate the human head in any respect except in essential dimensions. This device was constructed at NPL, with a view only to coupling the ear protector in a reproducible manner to a sound measuring device. The active component is a Brüel and Kjaer type 4153 artificial ear. This had been modified in the manner suggested by Johnston (3) whereby the flat plate normally used when measuring the response of circumaural earphones is replaced by a thicker plate, to reduce leakage effects. The artificial ear with microphone axis horizontal is backed by a pressed steel box which, acting as a spacer, provides the requisite width dimension. A wooden post is attached to provide a surface for the headband to rest on. No artificial skin is used.

The form and critical dimensions of the device proposed by ISO/TC43/SC1/WG17 are illustrated in Fig 1 c. It consists of a cylinder of diameter 140 mm machined from aluminium stock. The two end faces are inclined at an angle of 4° to the vertical as in the American Standard dummy head. A hole is bored in one of the end faces to accommodate a one-inch microphone. A Brüel and Kjaer type 4117 piezo-electric microphone was used. A cylindrical rod of diameter 25 mm forms the support for the headband of the test earmuff and the whole device is mounted on a resilient base.

4. EXPERIMENTAL ARRANGEMENTS

4.1 Sound field

The test sounds for diffuse field measurements consisted of 1/3-octave bands of noise, realized in the manner described in Appendix A of BS 5108. Four loudspeakers are positioned at the vertices of a regular tetrahedron with edges of length 2.7 m, each facing towards the centroid. The array was set up in a large free-field room. Each loudspeaker is fed from a separate channel having its own noise generator, 1/3-octave filter set and power amplifier. The channels were balanced and checks made on the uniformity and non-directionality of the sound field. The sound pressure level in each test band was always in the range 85 to 90 dB.

For some of the tests (see Section 6.3) a single loudspeaker was used, set up at a distance of 1.8 m from the device under test in the free-field room.

4.2 Measurement system

A Brüel and Kjaer type 2606 measurement amplifier situated close to the tetrahedral array was used to pre-amplify the output of the microphone in the dummy heads before transmission of the signal to a main measurement amplifier of similar type outside the free-field room.

Readings were made, in decibels relative to an arbitrary zero, using the flat weighting characteristic ('linear') of the measurement amplifier. When necessary these were related to absolute sound pressure levels by the use of a microphone calibrator.

5. MEASUREMENT METHOD

5.1 Preliminary measurements

5.1.1 *Noise floor*

The electrical noise in the measurement system was investigated by replacing the microphone capsule with its equivalent capacitance (4 nF). For this measurement the sound field was in operation so that any electrical pick-up in addition to instrumental noise would be detected. Each noise test band was switched on in turn and the signal observed.

The maximum noise level found was with the 125 Hz noise band in operation and was equivalent to a sound pressure level of 33 dB re 20 µPa. All levels measured in the course of the experiments exceeded this value by at least 10 dB.

The ambient noise in the free-field room is known to be very low (12) and was not a problem in the present studies.

5.1.2 *Acoustic isolation*

A factor to be considered in objective measurement methods is that of sound reaching the in-built microphone of the dummy head by paths flanking the earmuff, for example by structure-borne conduction or by entry to the rear of the microphone through the cable exit. Such leakage would result in spuriously low values of attenuation being recorded. It is necessary therefore to determine the maximum attenuation which can be measured (acoustic isolation) using, in place of a test earmuff, a cover of very high attenuation.

The Model 801 dummy head is supplied with such a device in the form of a thick-walled metal cup. The isolation was determined as the difference, for each test band, between the output of the microphone uncovered, and of the microphone covered with the metal cup, grease-sealed to the hard surface of the dummy head. Some difficulty was experienced in obtaining the best possible fitting of the cup and several series of measurements were taken. The American Standard specified acoustic isolation better than 60 dB in any frequency band in the range of interest (0.125 - 8 kHz). The values obtained here (Table 2) failed to meet the requirement in the 6.3 and 8 kHz bands, the measured isolations being 56 and 49 dB respectively.

Table 2

Acoustic isolation of dummy heads

Frequency (kHz)	Isolation (dB)		
	a	b	c
0.125	65	48	60
0.25	69	48	70
0.5	66	47	66
1	64	43	61
2	65	61	64
3.15	67	63	67
4	67	66	55
6.3	56	48	63
8	49	65	68

a American Standard dummy head (with artificial skin removed)

b Modified artificial ear (NPL)

c Provisional test fixture (ISO)

Specifications do not exist for the other devices used, but similar measurements were made on these. The results are given in Table 2.

None of the devices gave isolation figures of 60 dB or better at all frequencies. In the light of this some caution is necessary when considering the results from high attenuation earmuffs.

5.2 Measurement of attenuation

For diffuse-field tests, the dummy head was placed at the centroid of the tetrahedron, located as the point equidistant from all four loudspeakers. Markings were made on the base-plate to facilitate positioning and alignment of the head. Measurements were made in three orientations of the head to allow for imperfections in omni-directionality of the sound field. The orientations were chosen, by rotation about the vertical axis, as A facing away from a vertex, B at 90° to A, and C at 180° to A. Band sound pressure levels were measured at 1/3-octave centre frequencies of 0.125, 0.25, 0.5, 1, 2, 3.15, 4, 6.3 and 8 kHz. In tests where multiple runs at each orientation were made on each earcup to investigate the repeatability (see Section 6.1.4), the protector was removed and replaced between runs.

The method of fitting the earmuffs is important as it may considerably affect the results. For example, a bias towards high attenuation and over-optimistic repeatability may occur if fittings not within, say, 3 dB of the best value are rejected as inadequate. On the other hand it is clearly right to reject fittings with gross leaks, and the following compromise procedure was followed, intended to be the objective equivalent of the 'maximum attenuation consistent with reasonable comfort' criterion adopted for the previous subjective calibrations:

(1) extend the headband and place the earcups centrally on the sides of the dummy head.

(2) adjust the headband until it rests on the top support pillar.

(3) apply horizontal pressure to ensure that the pressure is spread evenly around the cushion.

(4) in the event of a gross leak (> 10 dB) being indicated by the meter reading of the preamplifier repeat the fitting procedure (sound field at a low frequency).

The test procedure for each pair of protectors was as follows:

(1) place dummy head in orientation A (B,C)

(2) 'open-ear' run (measurements at 9 frequencies)

(3) fit earmuffs, left earcup over microphone

(4) 'closed ear' runs 1, 2 and 3, removing and replacing earmuffs between runs

(5) repeat 2-4 for right earcup

(6) repeat 1-5 for next orientation.

6. RESULTS

6.1 Tests on American Standard dummy head

6.1.1 *Mean attenuation*

The earcup attenuation at each frequency was taken as the mean of the nine values recorded (3 replications in each of 3 orientations) and the standard deviations were also calculated. Table 3 shows these results.

It can be seen that there are some differences between the left and right earcups of the same earmuff, these being most marked for earmuff F. A t-test of these differences showed that 70% were significant at $P < 0.05$ and about 40% at $P < 0.001$. The significant differences were fairly evenly distributed over frequency and earmuff type. In Table 3, the average of the left and right earcups is omitted in cases where these differed by more than 5 dB. Subsequent tests on another sample of the type F earmuff gave much smaller left/right differences than the first sample tested, being similar to those found for types A, C, D and E, but as these tests were not made with all orientations and replications the results are not tabulated here.

Table 3

Attenuation of hearing protectors measured on
American Standard dummy head

Values for left and right earcups, and the means, in decibels
(Each value includes 3 replications at each of 3 orientations)

Frequency (kHz)		Hearing protector type									
		A		C		D		E		F	
		M	SD	M	SD	M	SD	M	SD	M	SD
0.125	L	4.3	1.0	10.6	0.5	31.3	2.0	13.3	1.6	11.7	2.0
	R	3.0	0.7	11.8	0.9	31.3	0.6	14.3	0.6	4.8	1.0
	$\overline{LR}$	3.6	1.1	11.2	0.9	31.3	1.5	13.8	1.3	*	-
0.25	L	2.3	0.5	21.8	0.2	31.7	0.5	16.7	2.1	20.2	0.2
	R	2.7	1.5	19.7	0.4	30.5	0.7	18.9	0.7	25.4	0.3
	$\overline{LR}$	2.5	1.1	20.8	1.1	31.5	0.8	17.8	1.9	*	-
0.5	L	15.3	0.8	38.1	0.3	32.6	1.0	25.8	1.7	33.6	0.6
	R	14.2	0.9	35.5	0.2	31.3	1.3	25.7	1.0	35.7	0.5
	$\overline{LR}$	14.7	1.0	36.8	1.4	31.9	1.3	25.7	1.4	34.7	1.2
1	L	24.3	0.5	49.1	0.8	46.0	0.2	36.6	0.9	43.5	0.8
	R	23.4	0.3	47.6	0.5	44.6	0.3	34.7	0.2	43.1	0.5
	$\overline{LR}$	23.8	0.6	48.3	1.0	45.3	0.8	35.7	1.2	43.3	0.7
2	L	35.2	1.0	42.8	1.4	52.5	1.2	46.7	0.9	53.5	1.7
	R	32.7	1.3	44.4	1.3	51.0	0.8	51.5	0.7	48.7	0.7
	$\overline{LR}$	34.0	1.7	43.6	1.5	51.8	1.2	49.1	2.6	51.1	2.8
3.15	L	39.7	1.8	38.6	1.7	48.1	1.7	45.7	2.1	53.6	3.3
	R	42.4	2.4	43.2	1.4	51.2	1.7	44.6	1.9	45.4	3.4
	$\overline{LR}$	41.0	2.5	40.9	2.8	49.7	2.3	45.2	2.0	*	-
4	L	38.4	2.1	38.8	1.5	51.5	1.7	43.3	2.2	48.8	1.6
	R	42.3	2.4	41.9	1.6	53.0	1.7	44.2	1.9	42.6	3.5
	$\overline{LR}$	40.4	2.9	40.3	2.2	52.3	1.9	43.8	2.1	*	-
6.3	L	38.0	2.8	39.5	2.4	39.8	3.5	40.3	4.0	38.3	2.1
	R	40.8	3.9	41.9	1.5	37.1	2.1	44.1	2.0	34.4	3.1
	$\overline{LR}$	39.4	3.6	40.7	2.3	38.4	3.2	42.2	2.7	36.4	3.3
8	L	39.7	0.7	41.3	1.6	46.4	1.4	37.8	3.3	42.6	2.0
	R	42.0	1.2	42.3	1.1	44.8	2.5	41.1	1.3	39.2	2.2
	$\overline{LR}$	40.8	1.5	41.8	1.4	45.6	2.1	39.5	3.0	40.9	2.7

* Average not taken when difference between L and R > 5 dB

6.1.2 *Dispersion of results*

The standard deviations given in Table 3 represent the overall uncertainty of the measurements. They are in general rather small at low frequencies (about 1 dB) and are larger (up to 4 dB) above 2 kHz. However the values include not only the repeatability but also the effect of changing the orientation of the dummy head in the sound field.

An analysis of variance was therefore made on each set of 9 data points to separate out variance due to systematic effects and hence estimate the random error inherent in the method. A 2-way analysis was performed, the data being examined for systematic variation between orientations (component σ_1^2) and between replications (component σ_2^2). There being 2 earcups on each of 5 protectors at 9 frequencies, this yielded 90 separate analyses.

The two components of variance were each tested for statistical significance against the residual (σ_0^2) using Fisher's F-test. A significant value of F for the between-replications variance σ_2^2 would imply a systematic temporal variation from the first to the third replication, as would occur if, for some reason, this last fitting was always the best. However, only 2 out of the 90 analyses showed a significant result at the 5% level, which is in line with a chance explanation. On the other hand, the between-orientations component σ_1^2 - a measure of the dependence of attenuation on orientation in the nominally diffuse field - was significant or highly significant in some 40% of cases. Each σ_2^2 component was therefore combined with its residual, and the variance ratio recalculated. The results again showed σ_1^2 attaining statistical significance in the majority of cases above 2 kHz.

Table 4 gives the components of variance σ_1^2 and σ_0^2 where the former is significant, together with the significance level. Where no systematic effects could be isolated the total variance is given.

These results, not unexpectedly, reflect some imperfections in the realization of a diffuse sound field which are most marked at the higher frequencies. Supplementary tests regarding this effect are described in Section 6.3.

6.1.3 *Comparison with real ear attenuation*

The results of subjective calibrations of the same specimens of hearing protectors, performed according to the standard threshold method of BS 5108 (1), were reported by Whittle and Robinson (12). The same method of

Table 4

Components of variance
(Values in dB^2)

Frequency (kHz)	Component	Hearing protector type A		C		D		E		F	
		Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
0.125	σ_0^2	1.0	0.2	0.2	0.9	4.2	0.4	2.7	0.3	4.1	1.0
	σ_1^2	–	0.3	–	–	–	–	–	–	–	–
	Sig	–	*	–	–	–	–	–	–	–	–
0.25	σ_0^2	0.2	2.1	0.0	0.1	0.2	0.5	4.6	0.3	0.0	0.1
	σ_1^2	–	–	–	–	–	–	–	0.4	–	–
	Sig	–	–	–	–	–	–	–	*	–	–
0.5	σ_0^2	0.6	0.8	0.1	0.0	1.0	1.7	2.9	1.0	0.4	0.1
	σ_1^2	–	–	–	–	–	–	–	–	–	0.2
	Sig	–	–	–	–	–	–	–	–	–	*
1	σ_0^2	0.2	0.1	0.1	0.3	0.0	0.1	0.8	0.1	0.7	0.1
	σ_1^2	–	–	0.6	–	–	–	–	–	–	0.2
	Sig	–	–	**	–	–	–	–	–	–	*
2	σ_0^2	0.9	0.3	2.1	1.6	0.3	0.6	0.3	0.5	0.9	0.2
	σ_1^2	–	1.7	–	–	1.7	–	0.7	–	2.6	0.4
	Sig	–	**	–	–	**	–	*	–	*	*
3.15	σ_0^2	0.2	5.7	0.3	2.0	0.1	0.1	1.7	0.4	10.6	11.7
	σ_1^2	3.9	–	3.5	–	3.7	3.6	3.7	4.2	–	–
	Sig	***	–	***	–	***	***	*	***	–	–
4	σ_0^2	1.4	5.7	0.6	0.3	0.2	0.6	1.8	0.9	2.7	4.5
	σ_1^2	3.9	–	2.1	3.2	3.8	3.2	4.2	3.6	–	10.6
	Sig	*	–	**	***	***	**	*	**	–	*
6.3	σ_0^2	7.8	1.4	0.2	0.5	0.1	0.4	7.1	1.9	1.2	3.1
	σ_1^2	–	18.0	7.1	2.3	16.6	5.5	12.2	2.8	4.2	8.5
	Sig	–	***	***	**	***	***	*	*	**	*
8	σ_0^2	0.5	1.4	0.3	1.2	0.1	6.5	11.0	0.6	0.9	1.7
	σ_1^2	–	–	2.9	–	2.4	–	–	1.5	4.2	3.9
	Sig	–	–	***	–	***	–	–	*	**	*

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

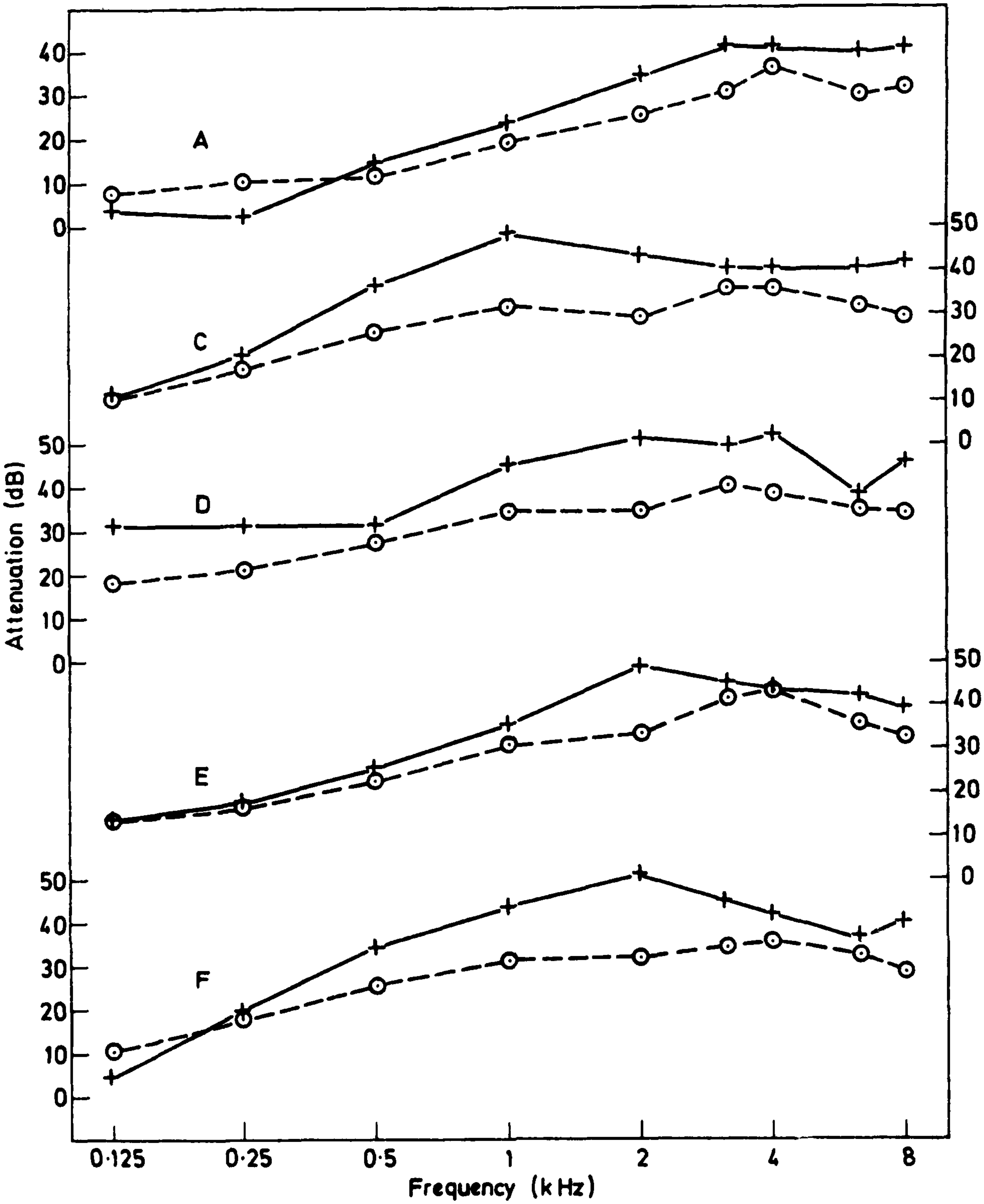

Fig 2. Comparison of real-ear and objective measurements

O - - - - O Real-ear (subjective)

+ ——— + Objective

realizing the diffuse sound field was used here, and a direct comparison is therefore possible between the sets of objective and subjective results. This is shown in Fig 2. The objective results are those given in Table 3 and are the mean of the right and left earcups, except where the difference is greater than 5 dB when the smaller value of attenuation is used.

The most obvious point of difference is in the magnitudes of the attenuation, the objective value being higher at all frequencies above 250 Hz for all earmuffs; the only exceptions occur at the lowest frequencies. The maximum difference is 19 dB and occurs at 2 kHz. Fig 3 shows the differences as a function of frequency for the five earmuffs, plotted to a larger scale. The curves are widely dispersed but there is a suggestion of underlying similarity. We return to a further discussion of these results in Section 7.2.

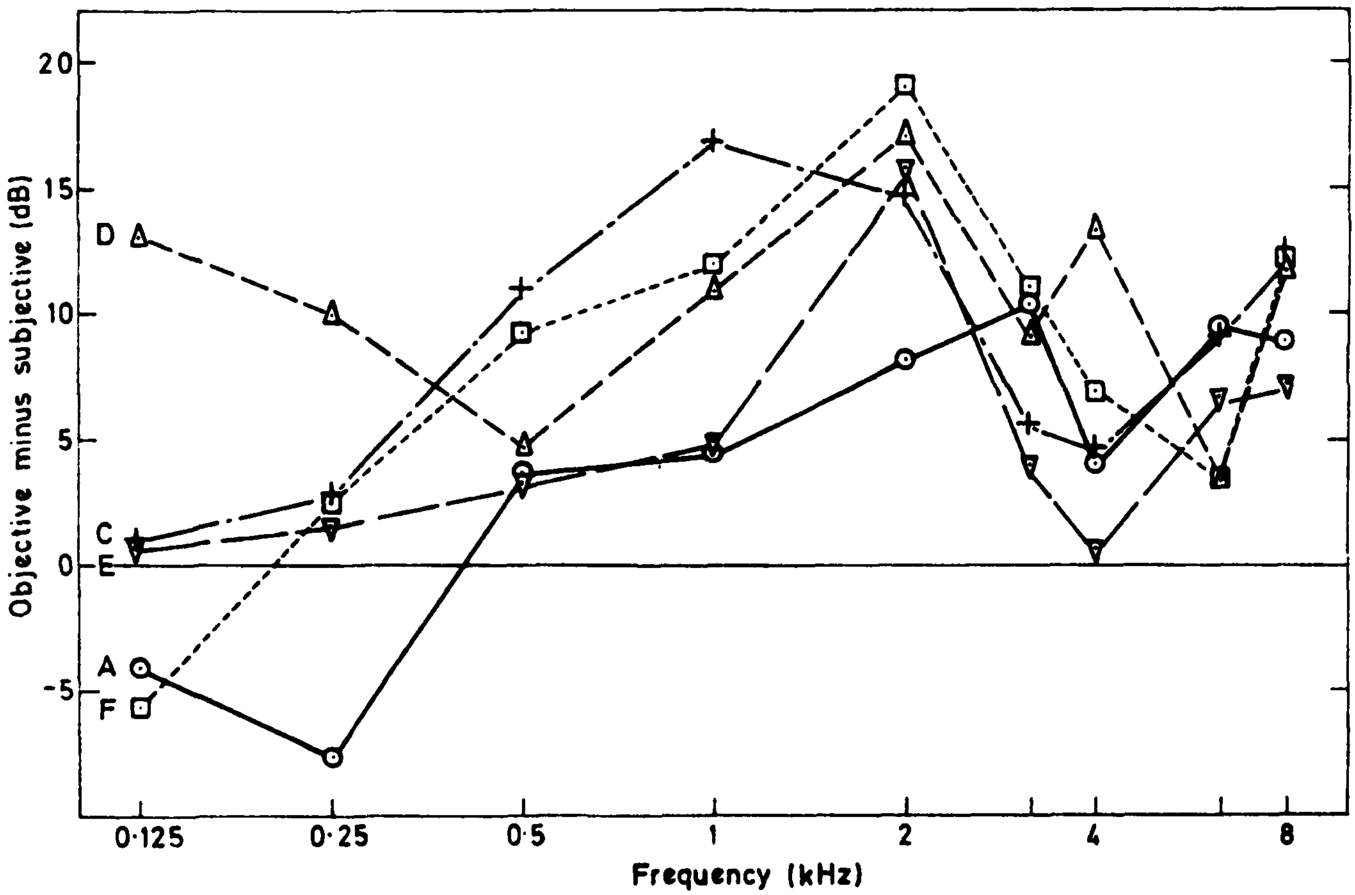

Fig 3. Objective-subjective differences for the five earmuffs tested

6.1.4 *Repeatability of objective measurements on American Standard dummy head*

The aspect of performance considered here is the variability associated with placement and replacement of the hearing protectors under test on the dummy head. To investigate it, variables associated with the sound field were eliminated so far as possible by leaving the dummy head in a fixed orientation with respect to the sound sources. 15 closed-ear readings were taken at each frequency, for the left earcup of each hearing protector. The muffs were removed, adjusted and replaced after each reading and (unlike previous results) no reading was rejected on the grounds of anomalously poor attenuation.

Table 5

Standard deviations on American Standard dummy head, with skin (dB)
(15 replications, one earcup, one orientation)

Frequency (kHz)	Hearing protector type					RMS
	A	C	D	E2	F	
0.125	0.8	1.1	1.1	2.6	0.5	1.42
0.25	0.8	0.3	0.4	1.4	0.3	0.77
0.5	1.0	0.3	0.4	1.2	0.3	0.75
1	0.6	1.2	0.2	0.8	0.1	0.71
2	1.1	1.7	0.7	0.5	0.5	1.01
3.15	1.8	1.7	0.3	1.2	1.2	1.35
4	1.6	2.3	0.4	0.4	0.6	1.31
6.3	0.4	1.1	1.1	1.3	0.8	0.99
8	0.8	3.6	0.4	0.7	0.9	1.74
RMS	1.08	1.77	0.64	1.28	0.66	Grand average 1.17

The standard deviations of the readings are given in Table 5. They range from 0.1 dB to 3.6 dB and the majority of them are below 1 dB. No marked trend with frequency is present in the results. A difference between the five types of earmuff may be distinguished but this is not clearly related to the type of seal (foam or fluid).

The results indicate that even with only a moderate number of replications, mean attenuation values with standard errors of 0.5 dB or less are readily attainable.

6.2 Effect of simplifying the dummy head construction

The use of artificial skin in the construction of a dummy head is motivated by the desire to improve the simulation of subjective results and perhaps also by the provision of a resilient seal to the earmuff in the expectation that this may give more reproducible results than a hard surface.

The results on Fig 3 show, however, that the simulation of the American Standard dummy head is far from perfect. On the other hand, if all that is required is accurate rank-ordering for quality control and similar purposes, the question arises whether it need be as complicated as it is to accomplish these ends. We therefore investigated the change in performance as a result of removing the artificial skin, both in respect of attenuation and of repeatability. In addition in section 6.2.2 simpler overall geometries are explored.

6.2.1 *Removal of artificial skin*

To explore this effect the artificial skin was removed from the dummy head and 15 attenuation measurements (refitting each time) were made under these conditions.

Table 6

Effect of removing artificial skin from American Standard dummy head
(Values are attenuation with skin minus attenuation without skin, in dB; average of 15 replications in each condition)

Frequency (kHz)	Hearing protector type					Mean
	A	C	D	E2	F	
0.125	1.1	-3.2	-5.0	-0.8	-0.7	-1.72
0.25	-3.7	1.3	-5.3	-3.8	1.6	-1.98
0.5	2.9	1.8	-3.3	2.4	1.7	1.10
1	2.3	-3.5	-2.6	0.1	-2.2	-1.18
2	-2.4	-0.3	1.5	0.3	0.4	-0.10
3.15	2.7	0.5	-0.3	0.7	0.6	0.84
4	1.2	1.2	0.8	0.9	-1.3	0.56
6.3	0.6	-1.5	-2.3	2.6	-0.3	-0.18
8	1.3	-3.1	2.6	-0.4	0.0	0.08
Mean	0.67	-0.76	-1.54	0.22	-0.02	Grand mean -0.29

Five earmuffs were used for these tests (A, C, F, foam type; and D, E2, fluid type), four being the same as previously and the fifth (E2) a replacement of the same type for the protector which had been discarded. For these tests, the muffs sealed directly on to the flat aluminium surface around the microphone.

The results were compared directly with those with the skin in place (Table 6). Attenuation values without the skin ranged from 5.3 dB better to 2.9 dB worse at different frequencies, but without any systematic relationship to frequency or earmuff type. The grand average values differed only by 0.3 dB.

Standard deviations of replication of the measurements, in the absence of the artificial skin, are given in Table 7, which should be compared with Table 5 for the unmodified dummy head. The difference is surprisingly small, sometimes in favour of one condition and sometimes the other. The grand average values of 1.17 and 1.07 dB can be considered virtually identical.

Table 7

Standard deviations on American Standard dummy head, without skin (dB)
(15 replications, one earcup, one orientation)

Frequency (kHz)	Hearing protector type					RMS
	A	C	D	E2	F	
0.125	1.1	1.0	1.0	1.9	0.5	1.19
0.25	0.6	0.6	0.5	1.5	0.7	0.86
0.5	0.5	0.3	0.3	1.4	0.3	0.70
1	0.5	1.9	0.6	1.3	0.8	1.14
2	0.5	2.1	0.8	0.6	0.2	1.07
3.15	0.8	1.7	0.3	0.7	1.5	1.13
4	1.3	2.1	0.3	0.4	1.6	1.33
6.3	0.6	0.8	0.5	0.9	0.5	0.68
8	0.6	2.3	0.6	1.5	0.6	1.31
RMS	0.77	1.59	0.59	1.23	0.88	Grand average 1.07

6.2.2 *Effect of head shape*

This aspect was studied by comparing the attenuations obtained on three devices. One was the American Standard dummy head, modified by removal of the artificial skin. The other two were as described in Section 3.2; one of them a simple rectangular box attached to an artificial ear, and the other a circular cylinder with slightly oblique end faces.

For these tests, two pairs of earmuffs were used, type A (foam-filled seal) and type E2 (fluid-filled seal). They were carried out at 3 orientations in the diffuse field, 3 replications for each orientation, and for both earmuffs of each pair.

Results are shown in Fig 4 and it is obvious that the overall geometry of a dummy head is not a critical factor.

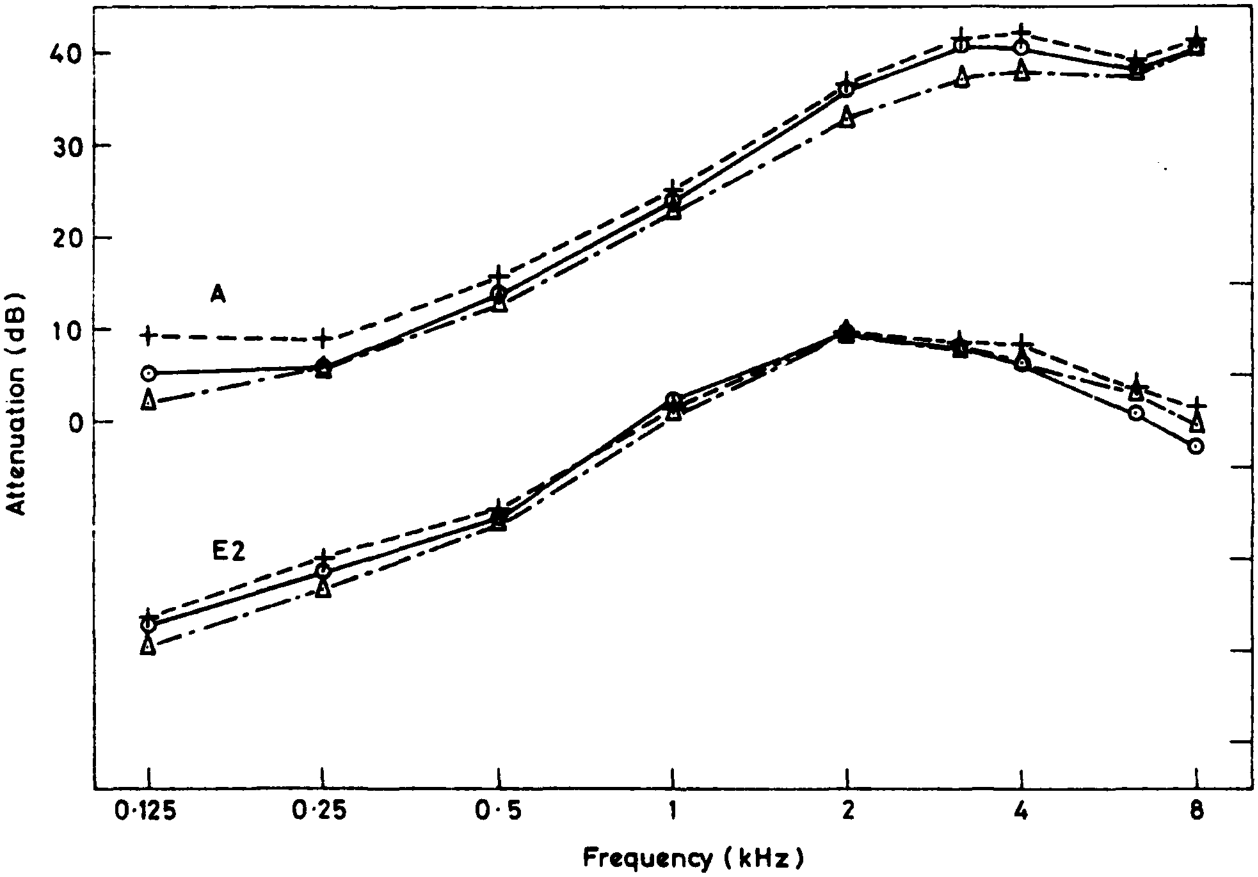

Fig 4. Comparison of attenuation measured on three dummy heads (mean of 3 orientations)

O ——— O American Standard device

Δ — — — Δ Modified artificial ear (NPL)

\+ - - - - + Provisional test fixture (ISO)

6.3 Effect of sound field configuration on results of objective measurements

The results so far described point to the possibility of using one or other of the simple dummy heads as a comparator device. In the practical application, one could envisage the need to adopt a simplified sound field configuration in keeping with the simplified nature of the test fixture, rather than the complicated tetrahedral multichannel reproducing system required for the subjective test procedure. Nor would this complication be necessary, since a diffuse field suitable for objective tests (but not for real-ear threshold work) can more easily be obtained in a reverberation room. On the other hand even a reverberation room might be a needlessly elaborate and expensive requirement. The question arises whether a simple plane-wave test employing an acoustic duct could be substituted, thus circumventing the need for a large acoustic test chamber. Such a project is under consideration by the ISO working group.

Measurements were made in the large free-field room to explore the directional variations of attenuation in azimuth.

The tests were made with 5 muffs (A,C,D,E2,F) using the unmodified American Standard dummy head, first in the diffuse field (tetrahedral source array) and then in line with the axis of a single loudspeaker in a separate set-up. The test objects were rotated continuously on a turntable, in the two conditions: muff absent, left muff measured.

The angular variations differed considerably between the five earmuffs, both as regards principal and fine structure. In order to present useful comparisons these variations have been expressed as standard deviations in decibels about the mean azimuthal value obtained from 36 readings at 10° intervals for each muff at each frequency. The results are illustrated in Fig 5. They show that the choice of a single orientation in a plane-wave test would be likely to result in an uncertainty of effective attenuation of the order 5 dB, and in fact azimuthal variations of as much as 24 dB occurred for one of the muffs at 2 kHz, despite the use of bands of noise 1/3-octave wide.

In a truly diffuse field, the azimuthal variations would vanish and the curves of Fig 5 would collapse to the abscissa. The sound field configuration produced by the tetrahedral array of 4 non-coherent sources does not fully achieve this, but is nevertheless fairly successful at approximating the diffuse condition, as judged by the fact that it reduces the angular variation by a factor of about 4 compared to the plane wave condition.

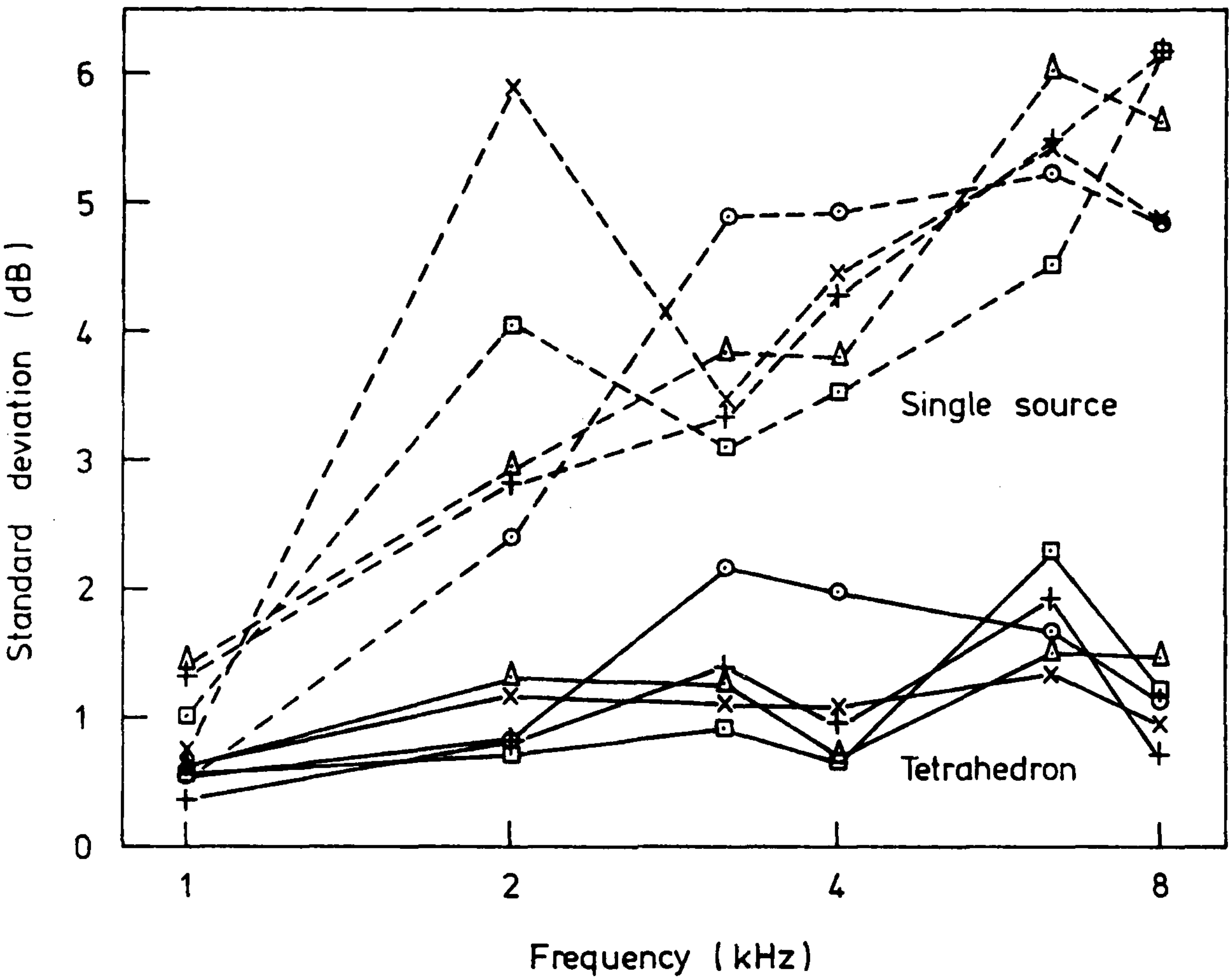

Fig 5. Variability of objective attenuation in azimuth

7. DISCUSSION

7.1 Components of variance

The experiments described in Sections 6.1.2, 6.1.4 and 6.3 provide a cross-check on the components of variance in objective measurements using the American Standard dummy head. In Table 3 the total variance is estimated on the basis of 9 measurements (3 orientations x 3 replications) for each frequency on five ear protectors. Table 4 shows that part of this variance can be attributed to orientation of the dummy head with respect to the loudspeaker array, and Fig 5 shows the results of systematic tests to explore this effect. Furthermore, the replication variance has been examined in an independent series of tests summarized in Table 5.

It is instructive to compare the sum of the separate component variances with the total variance found in the overall tests (Table 3). The common items in this 3-part comparison are the American Standard dummy head (unmodified),

Table 8

Comparison of component and total variances (dB^2)
(rounded to nearest 0.1)

Source of variance	Frequency (kHz)	Ear protector type				Mean of ACDF
		A	C	D	F	
Replication	1	0.4	1.4	0.1	0.0	0.5
	2	1.2	2.9	0.5	0.3	1.2
	3.15	3.2	2.9	0.1	1.4	1.9
	4	2.6	5.3	0.2	0.4	2.1
	6.3	0.2	1.2	1.2	0.6	0.8
	8	0.6	12.9	0.2	0.8	3.6
	Mean	-	-	-	-	1.7
Orientation	1	0.3	0.4	0.3	0.4	0.3
	2	0.7	1.7	0.6	1.5	1.1
	3.15	4.8	1.6	0.8	1.3	2.1
	4	4.0	0.5	0.5	1.0	1.5
	6.3	2.9	2.4	5.4	1.9	3.2
	8	1.3	2.3	1.5	0.5	1.4
	Mean	-	-	-	-	1.6
Sum of replication and orientation	1	0.6	1.8	0.4	0.4	0.8
	2	1.9	4.6	1.1	1.7	2.3
	3.15	8.0	4.5	0.9	2.7	4.1
	4	6.5	5.8	0.6	1.3	3.6
	6.3	3.0	3.6	6.6	2.6	4.0
	8	2.0	15.2	1.7	1.3	5.0
	Mean	3.7	5.9	1.9	1.7	3.3
Overall	1	0.3	0.6	0.0	0.6	0.4
	2	1.0	2.0	1.4	2.9	1.8
	3.15	3.2	2.9	2.9	10.9	5.0
	4	4.4	2.3	2.9	2.6	3.0
	6.3	7.8	5.8	12.2	4.4	7.5
	8	0.5	2.6	2.0	4.0	2.3
	Mean	2.9	2.7	3.6	4.2	3.3
Variance ratio (Sum/overall, or reciprocal)	Mean/mean	1.3	2.2	1.9	2.5	1.0
DF		6/6	6/6	6/6	6/6	24/24
Significance level		NS	NS	NS	NS	NS

the tetrahedral sound source array, the frequencies from 1 to 8 kHz inclusive and the left members of four pairs of protectors (A, C, D, F) The fifth ear protector (type E) has been omitted from the analysis because two examples of this type were involved in different legs of the triangle.

The comparison is shown in Table 8. For individual frequencies and individual ear protectors agreement between the overall variance and the sum of the replication and orientation components is lacking. Indeed it is hardly to be expected, because the orientations did not occur randomly in the overall measurements. However, the grand average values across protectors and frequencies are in excellent accord, and the two components are seen to be almost equal (1.7, 1.6 dB^2). In the ensemble of earmuff types and frequencies the effect of orientation is no doubt adequately randomized.

It is clear that the overall variance could be reduced, by perhaps 1 dB^2, if the diffuse field simulation were improved (for example, by using a reverberation room) but the gain, in terms of overall uncertainty in an objective measurement of ear protector attenuation, could at best be slight. For muffs which exhibit a replication uncertainty larger than the average (such as type C of the present tests), the orientation variance would represent only a small fraction of the total and little or nothing would be gained by reducing it. For well-repeating muffs (such as type D) the overall uncertainty is already sufficiently small as to be acceptable for practical purposes. These conclusions would not necessarily be true if tests were made in plane-wave conditions.

7.2 Objective-subjective comparison

The comparison between subjective attenuation and the objective attenuation measured on the American Standard dummy head, illustrated in Figs 2 and 3, whilst not providing an ideal one-to-one relationship, showed enough similarity in the results from the different earmuffs tested to merit further investigation.

This was made in the form of linear regressions of subjective against objective attenuation for the individual frequencies. The results are given in Table 9, using alternative values - 'M or L' or 'L' for the objective attenuation, as described at the foot of the table. The regression lines and data points for the 'L' case are illustrated in Fig 6. Correlation coefficients at frequencies up to and including 2 kHz are all greater than 0.9 ($P < 0.05$), but little reliability can be attached to the results at higher frequencies.

Table 9

Linear regression of subjective on objective attenuation (5 earmuffs)

Frequency (kHz)		Correlation coefficient	Slope	Intercept (dB)	Range of objective data (dB)
0.125	M or L* L†	0.96 0.97	0.35 0.34	7.5 7.7	3-32
0.25	M or L L	1.00 1.00	0.38 0.39	9.5 9.5	2-31
0.5	M or L L	0.94 0.95	0.69 0.73	2.5 2.0	14-36
1	M or L L	0.91 0.90	0.54 0.53	8.4 8.9	23-48
2	M or L L	0.96 0.95	0.46 0.48	9.6 9.7	32-51
3.15	M or L L	0.71 0.66	0.87 0.73	-2.1 4.8	38-49
4	M or L L	0.37 0.39	0.24 0.24	27.6 27.8	38-52
6.3	M or L L	0.23 0.16	0.25 0.17	23.3 26.7	34-41
8	M or L L	0.44 0.40	0.40 0.32	14.7 18.6	37-45

*M or L is the mean of left and right earcups, except when the L/R difference is greater than 5 dB when the lower value is taken.

†L is the lower attenuation value of the two earcups.

It seemed worthwhile, since we had available a further earmuff which had just been subjectively tested according to BS 5108, to attempt a prediction of these test results. Objective measurements were carried out as before and a prediction was made from the regression coefficients (Table 9) using the 'L' data. The comparison of predicted and actual subjective attenuation is given in Table 10, which shows the average prediction error to be about -0.5 dB, the largest value being 3.4 dB at 125 Hz. Prediction using the 'M or L' figures was very similar.

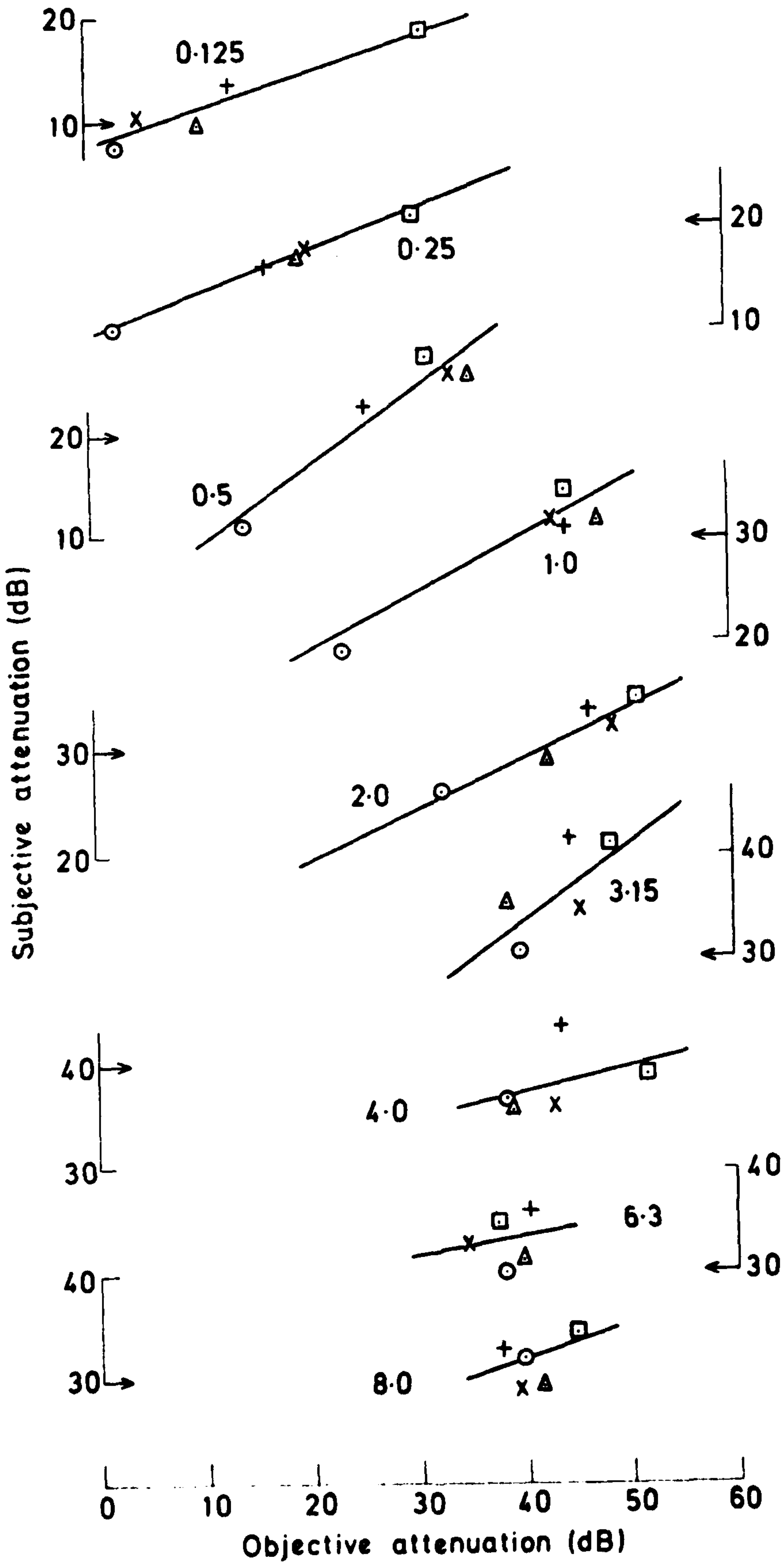

Fig 6. Subjective against objective attenuation for five earmuffs

Table 10

Comparison of predicted and measured
subjective attenuation of a hearing protector

Frequency (kHz)	Objective attenuation* (dB)		Subjective attenuation (dB)		Error of prediction (dB)
	Left	Right	Predicted	Measured	
0.125	<u>2.2</u>	3.5	8.4	11.8	-3.4
0.25	<u>10.5</u>	11.0	13.6	12.6	+1.0
0.5	<u>26.0</u>	26.0	21.0	19.6	+1.4
1	35.1	<u>34.8</u>	27.5	26.1	+1.4
2	46.9	<u>46.3</u>	31.9	32.0	-0.1
3.15	<u>44.9</u>	46.5	37.1	39.3	-2.2
4	<u>44.1</u>	46.5	38.4	38.0	+0.4
6.3	<u>37.6</u>	39.6	33.1	33.7	-0.6
8	<u>37.7</u>	39.6	30.7	32.6	-1.9
				RMS	1.68

*underlining indicates value used for prediction

We have treated the data in a purely empirical fashion, and advance no theoretical reasons as to why the subjective values cover a narrower range than their objective counterparts. Clearly we have not sufficient data here to postulate a general relationship, and the range of our data happens to be rather limited at the higher frequencies. In time, however, systematic gathering of data on a wide variety of muffs using both subjective and objective methods would enable the regression to be derived more reliably, perhaps leading to eventual abandonment of subjective testing.

8. CONCLUSIONS

We have speculated in the above section that the subjective-objective correlations may one day be sufficiently well-determined and accurate to make subjective testing superfluous. For the present, however, we regard the use of the subjective method as inescapable and decisive for type testing of hearing protectors. Irrespective of accurate simulation of subjective performance, the use of a dummy head has an important role in production quality control and for in-service checks to ensure that initial levels of performance are maintained. These applications change the emphasis to reproducibility of results, rapidity of test, and cost.

Our tests indicate that there is little to be gained in terms of repeatability by the use of artificial skin. The device would be easier to specify and probably more consistent in long-term use by dispensing with this feature.

An important property of a dummy head is its acoustic isolation, the desirable value of 60 dB at all frequencies not being fully met with any of the devices tested here. It seems probable however that simple modification to the sealing arrangements and the substitution of a condenser microphone for the piezo-electric type would enable the desired isolation to be obtained.

The work described here has underlined the need for a decision on a criterion to be used for handling repeated objective results to obtain suitable confidence limits on the attenuation. We have found distributions which are often very skewed and sometimes bimodal. Where such variability results from faults in the design or condition of an earmuff, as opposed to experimental uncertainties, it must somehow be included in the evaluation and description of performance. This aspect needs further investigation.

Finally the objective test method should include a specification of the type of sound field to be used. Decision on this must await the outcome of deliberations of the ISO working group, but the possible pitfalls in any directional sound field are clear. One promising line of approach involves a simplified form of diffuse sound field generated in a small enclosure of a few cubic metres. This would produce a non-critical sound field and have the added advantages of closer approximation to real-ear testing procedures and of simpler specification and construction than plane-wave methods.

9. ACKNOWLEDGEMENTS

The authors are grateful to Mr K.S. Fancey who contributed to the work with ideas and experimental assistance.

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The aspect of performance considered here is the variability associated with placement and replacement of the hearing protectors under test on the